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TOPOLOGY OPTIMIZATION OF MACHINE ELEMENTS

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Abstract: *The paper presents a topology optimization procedure for the machine elements design. The procedure uses a CAD-CAE environment. Model preparation for design optimization is simple and fast and multiple checks assure a good mesh quality. After optimization geometry reconstruction using mesh pattern is done to obtain a smoothed surface. Results are compared with other attempts available in recent literature. Remarks regarding model preparation, as well as efficient optimization procedures have been done.*

Key words: *optimization, topology, design, mesh, geometry, reconstruction.*

1. INTRODUCTION

Design optimization is a technique based on the finite element method, which generates concept design proposals from supplied packaging information. Main optimization targets are: maximum stiffness; highest possible natural frequency; minimum weight and maximum allowable stress.

In mechanical design four optimization procedures are available at present: • topology [1] optimization (Fig. 1), which means best material distribution; • topography optimization (Fig. 2), determining sampling patterns in thin walled components; • shape [2] optimization (Fig. 3), improving the local shape of existing components and • parameter optimization (Fig. 4), which determines the best ratio between different structural parameters or allows sizing the components. Solutions based only on designer experience are reviewed.

Studies regarding the integration of the optimization procedures in the design chain have been reported in recent literature [3, 4, 5, 6], emphasizing the importance of the topic in mechanical engineering research.

Most of the attempts used the two solutions available on the software market today for including optimization in the design cycle: TOSCA system, from FE-DESIGN GmbH in Karlsruhe, Germany [7], that works in relation with different FEM solvers, and Altair Optistruct, from Altair Engineering USA, which has his own optimization solver. Although the results are encouraging o lot of manual work has still to be done in model preparation.

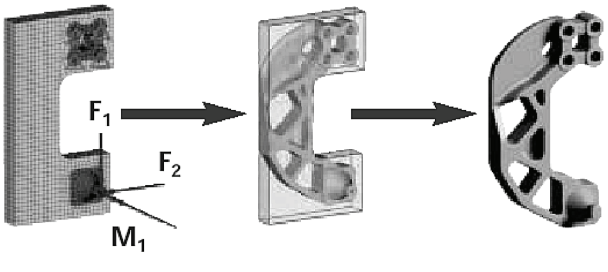

Fig. 1. Topology optimization.

Fig. 2. Topography optimization.

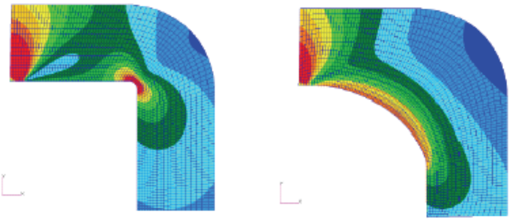

Fig. 3. Shape optimization.

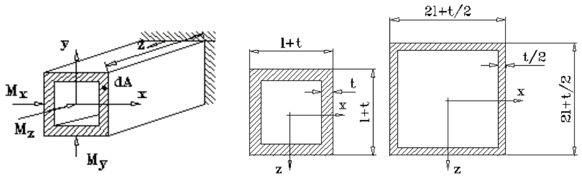

Fig. 4. Parameter optimization.

The present paper proposes a topology optimization procedure to improve mechanical component design. The procedure uses a CAD-CAE environment and offers complete control on model preparation and geometry reconstruction. The number of transfer steps is reduced and the functionalities of CAE translators are used. The procedure is simple and fast and multiple load cases, as well as different types of analysis are allowed.

2. REMARKS REGARDING TOPOLOGY OPTIMIZATION

Topology optimization is a technique used to determine the optimal material distribution in a given design-space considering given restrictions and loadings. It removes material from the defined design space, which has to be considered as a geometric space envelope containing the final design proposal.

The SIMP algorithm (Solid Isotropic Microstructure with Penalty for intermediate densities) seeks to minimize the structural compliance energy U_c, which represents in fact the objective function [8, 9]. The design variables are internal pseudodensities η_i assigned to each finite element *i*.

For a 3D problem and in the linear-elastic domain the compliance $[D]^{-1}$ represents the inverted elasticity matrix $[D]$, which relates the stress vector $\{\sigma\}$ with the strains vector, as known from the theory of elasticity:

$$\{\sigma\} = [D]\{\varepsilon\}, \tag{1}$$

$$[D_{x-y-z}]^{-1} = \begin{bmatrix} 1/E_x & -\upsilon_{xy}/E_y & -\upsilon_{xz}/E_z \\ -\upsilon_{yx}/E_x & 1/E_y & -\upsilon_{yz}/E_z \\ -\upsilon_{zx}/E_x & -\upsilon_{zy}/E_y & 1/E_z \end{bmatrix} \tag{2}$$

The elementary pseudodensities η_I vary between 0 and 1. The elements for which $\eta_i \cong o$ represent the material that have to be removed, and the elements for which $\eta_i \cong 1$ represent parts where the material that has to be maintained.

The mathematical form of the optimization problem in this case is:

$$U_c = \min \quad 0 < \eta_i < 1 \ (i = 1, 2 \ldots N), \tag{3}$$

where N represents the number of finite elements. The total volume of the structure V is computed after each iteration

$$V = V_0 - V^*, \tag{4}$$

where V_0 is the initial volume and V^* the amount of material that has been removed. The total structural volume is computed as the sum of element volumes, that means:

$$V = \sum_i \eta_i V_i, \tag{5}$$

where V_i is the volume of element *i*.

While the structural compliance energy U_c and the total volume V are global conditions, for each finite element calculations are done for estimating elementary pseudodensities.

Internal pseudodensities affect the volume and the elastic vector for each finite element

$$[E_i] = [E(\eta_i)]. \tag{6}$$

Topological optimization can be applied for a single load case or for simultaneously multiple load cases. For k different load cases, the weighted function is

$$F(U_c^1, U_c^2, \ldots, U_c^3) = \sum_{i=1}^{k} w_i U_c^i, \tag{7}$$

where w_i is the weight for the load case with structural compliance energy U_c^i. The objective function U_c is replaced in this case with the F function.

3. PROBLEM DESCRIPTION

For a structural machine component a topology optimization attempt is illustrated together with the related software in Fig. 5 to Fig. 9. The component is a supporting element subjected to two load cases: bending in the vertical plane and compression in the horizontal one.

In the first step the CAD system was used to create a draft solution (Fig. 5), based on a list of specifications and to define the loads and constraints (Fig. 6). It was also necessary to know the stiffness requirements for the component. On the basis of this information the part topology was optimized automatically producing a first oriented draft design (Fig. 7). A 40% of the initial material was removed without loosing stiffness.

The objective of further processing was to approximate the step-like shape of the component with a smoothed one, which means in fact geometry reconstruction (Fig. 8). Finally, the component was checked (Fig. 9) and the geometry was conceived in a CAD format.

Because no manufacturing restrictions were imposed the solver created small non material regions in the inside of the component. If the part is manufactured through cutting procedures, this shape is difficult to obtain. In this study geometry reconstruction procedures after topology optimization and solutions for reduced transfers between systems were the main purposes. As such, the complex geometry was appropriate and the

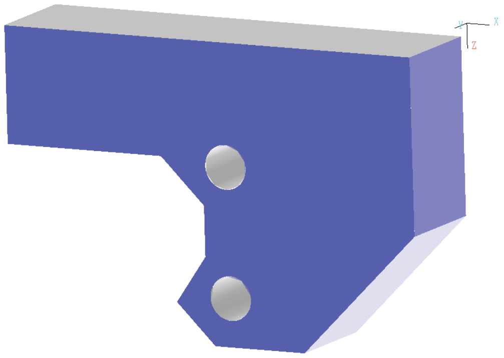

Fig. 5. CAD model.

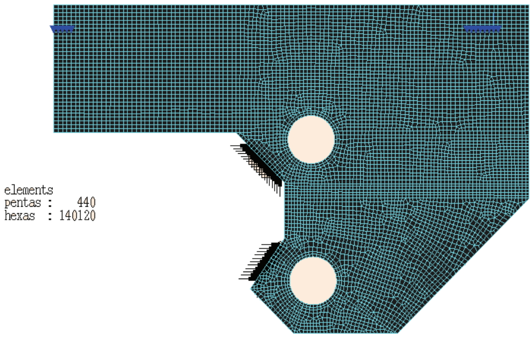

Fig. 6. Mesh preparation. Preprocessing system.

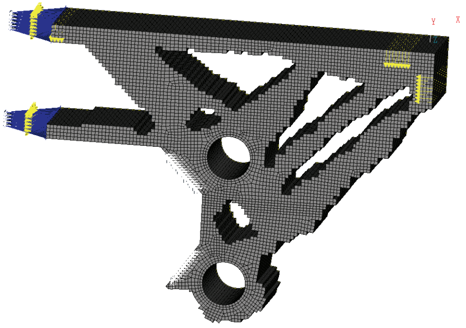

Fig. 7. First oriented draft design. Solver exit.

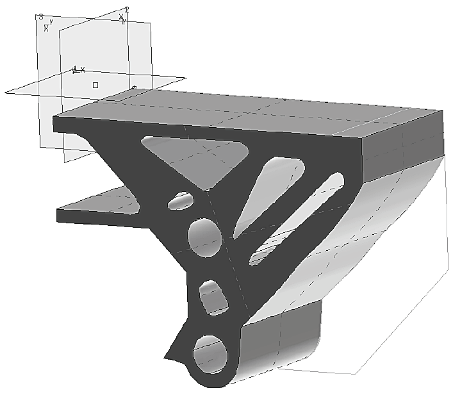

Fig. 8. Smoothed model. Preprocessing system.

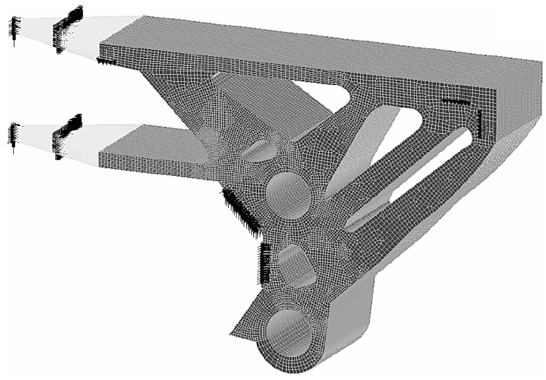

Fig. 9. Mesh preparation for final verification. Preprocessor.

model was further processed in order to obtain the isosurfaces and to convert it in a compatible CAD format.

3.2. Model preparation

The geometry of the supporting element (Fig. 5) was created in CATIA V5 and exported to ANSA-CAE-Translator [10, 11] with an IGS format. The preparation strategy used additional cuts, offsets and curves creation in order to avoid tetrahedral elements and to assure a sufficiently fine mesh for the computational algorithm (Fig. 7). The mesh was refined in the neighborhood of the surfaces coming in contact with other parts and frozen elements were declared. Special boundary conditions were imposed.

3.3. Geometry reconstruction

Because topology optimization procedure mainly deletes elements that are not in the load flow, the model needs to be smoothed and the geometry reconstructed after obtaining a load-oriented draft design. Figs. 10 and 11 show two recovering stages for obtaining the new 3D geometry. The model was entirely processed in the CAE Translator, so it was not necessary to return in the CAD system.

If not all the faces are modified, information about the initial geometry is very useful at this point. Parts of the initial mesh pattern can be saved using the PreProcessing system functionalities [12]. In this case the geometry is overlaid on the mesh, but not connected with it. Further, a paste function can connect them, if required.

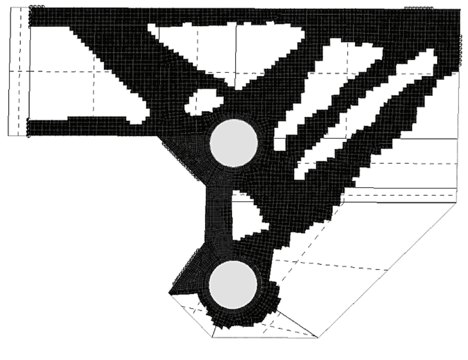

Fig. 10. Draft model.

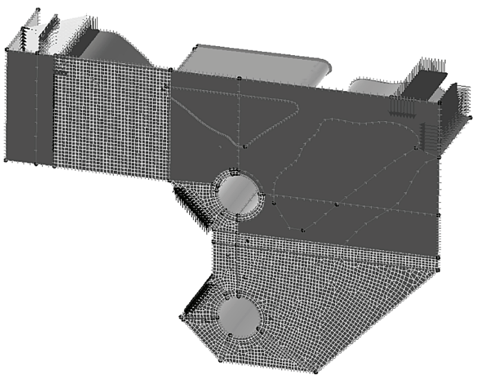

Fig. 11. Mesh pattern and new smoothed curves.

The geometry can be observed deactivating the visibility of the finite element model.

Each face corresponds to a macro area retaining the mesh configuration. Other faces have been created using smoothed curves (Fig. 11).

Another option is to create 3D curves from selected edge lines of the meshed model. Than the PreProcessor automatically generates faces from the 3D wireframe description. The mesh pattern can be kept by projecting curves on surfaces, if required.

PreProcessing systems requirements for model reconstruction after topology optimization are:

- calculation of the isosurfaces of the model;
- transformation and data reduction; export in the CAD compatible formats, such STL and IGES;
- export as VRML for fast 3D visualization;
- export as FE mesh for remeshing and analyzing;
- translate the mesh for different solvers.

4. TOPOLOGY OPTIMIZATION IN THE DESIGN CHAIN

Topology optimization was developed because the change of shape and size may not lead in weight reduction and it was primary used in the automotive, aerospace industry and in biomechanics. The aim of integrating topology in the design process is to automate load-oriented design and make it faster.

The process consists of several steps, starting from design space definition over CAD-modeling, generation of the FE-mesh using a preprocessor, in order to initiate topology optimization.

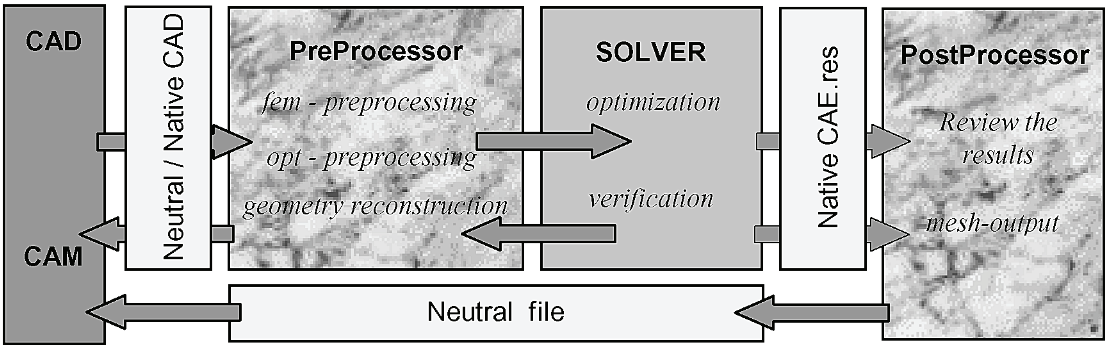

Fig. 12. Integration of CAD-CAE tools in the design process.

After topology optimization, the design model is no longer purely based on geometrical data. Therefore, this step-like-shape model has to be smoothed using a special smoothing algorithm in order to gain a smooth, geometrically definite surface. The optimization process ends with the transformation of the shape-optimized data into a geometry-based CAD model.

For all the conversion steps, the whole chain of CAE modeling processes has to be considered. The user do not have to leave this chain (CAD → CAE / Optimization → CAD) from the rough drafts to the final detail improvements. Therefore, a wide variety of links and interfaces between several engineering software tools are available for generating and evaluating numerical models, such as FE Pre- and Postprocessors.

Fig. 12 shows how the different modules, such as the Solver, Pre- and Postprocessor, CAD-CAM System have to interact in an integrated optimization system.

5. CONCLUSION

Optimization methods are useful design tools for economical reasons. A real design environment based on an optimization algorithm must be user-friendly and has to allow including manufacturing restrictions when looking for the best material distribution. This is easier if the solver supports a parametrical design language input. Model preparation for final verifications is simple and fast if the optimized geometry is constructed using the initial mesh pattern.

Because topology optimization is done in an early stage of the design it is important to obtain a rapid smoothed shape in the geometry reconstruction stage. When CAE PreProcessor is used for geometry recovering no topology cleaning operations are necessary in model preparation.

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